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Mechanical and Sustainable Performance of Polyester Composites with Glass and Natural Waste Fiber Fillers

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Abstract

This study investigates the development and mechanical performance of unsaturated polyester composites reinforced with natural fillers, ground walnut shells, tree leaves, and woven fiberglass. The objective is to evaluate the effectiveness of these eco-friendly, recyclable materials in enhancing structural properties and promoting sustainable waste management. Composite samples were fabricated using compression molding and hand lay-up techniques, with natural fillers at 10 wt.% and 20 wt.%, and reinforced with one or two layers of fiberglass mats. Mechanical testing, including tensile and flexural evaluations, followed ASTM standards. Results showed that incorporating one and two layers of woven fiberglass improved tensile strength by 44% and 81%, and flexural strength by 32.2% and 48.3%, respectively, compared to neat polyester. These improvements are attributed to acid-base surface interactions and the high surface energy of glass fibers, enhancing fiber–matrix adhesion. Among natural fillers, walnut shell powder outperformed tree leaves, particularly in hybrid composites. However, the addition of natural fillers to fiberglass-reinforced composites reduced strength due to weaker interfacial bonding and non-uniform dispersion. An optimal filler content of 20 wt.% was identified for balancing performance and processability. These findings highlight the importance of filler type, content, and fiber configuration in designing sustainable hybrid polyester composites.

Keywords: Eco-friendly, Flexural strength, Hybrid, Mechanical properties, Natural Fiber.

1. Introduction

Production of environmentally friendly, sustainable materials has become an important objective of the struggle against ecological degradation and optimization of resources [1]-[3]. In a bid to respond to the increasing environmental issues, composites of partially natural fibers have been made in which plastic polymer matrices are used together with natural reinforcements. Even though synthetic fiber composites usually offer better mechanical and thermal characteristics, their non-biodegradability is a difficulty for sustainability and a source of pollution [4]. Consequently, more and more focus has been placed on the creation of partially green composites, which consist of synthetic matrices mixed with biodegradable fillers, and on the characterization of their mechanics. In order to improve performance further, scholars have studied hybrid composites, assembled by a combination of two forms of reinforcements, i.e., natural/natural or natural/synthetic, in one polymer matrix [5]-[8]. Many of the previous studies on hybrid composites involving both natural and synthetic fibers cover a wide variety of topics. Though they have been appreciated due to their affordability, eco-friendliness, and availability, researchers have indicated some of their weaknesses, including their low thermal stability and high water absorption. [9]-[11]. This will reinforce, harden, and increase resistance to impacts among others [12]-[14]. The key factors to consider to replicate the mechanical properties of the synthetic fiber composites are fiber orientation, weight fraction, and stacking sequence, as revealed in research [15], [16]

The content of fiber in the composite material has a significant effect on the mechanical properties. The densities, hardness, flexural strength, modulus of elasticity, and yield strengths of a material can be advanced by adding various forms of fibers [6]. The fiber orientation, weight fraction, and stacking sequence are all important considerations in hybrid composites to produce mechanical properties comparable to those of synthetic fiber composites. [17]-[21]. Due to their capacity to enhance mechanical properties, cost-effectiveness, and eco-friendliness, recycled and organic fibers in polymer composites have become a growing trend in the past few years. Fibers of bananas, pineapples, coir, and rice straw are only a few of the potential reinforcing materials that have been examined by researchers to be used in polymer composites. Such studies indicate that individuals are seeking new applications of old materials more and more. Not only does this utilise these organic waste products in a superior way, but it also adheres to the sustainability guidelines [4] and [7]. Mirzamohammadi et al. [22] examined the effect on the impact and bending characteristics of environmentally friendly metal/composite laminates made by hybridizing natural fibers with montmorillonite nanoparticles. They found that these qualities were improved, which shows that adding nanoparticles and natural fiber reinforcements could be helpful. Naik et al. [23] found that thermosetting composites reinforced with bio-fillers, such as orange-peel particles, improved mechanical behavior, including flexural and tensile characteristics. Nayeeif et al. [24] demonstrated an enhancement in the bending strength of polyester composites by incorporating waste natural fibers, such as sawdust and eggshells, into the material. Hamdan et al. [25] examined compression stress and other structural features of the natural composites made of walnut peels, sawdust, and polyester, which were recycled. The researchers were able to find out that the elastic modulus of polyester was improved with the introduction of 10 percent of these natural fibers; in further studies, researchers observed that natural compounds varied in hardness and that compression stress was reduced in the presence of water, salt, and acid. Pani and Mishra [26] studied the hybrid polymer composites that are strengthened with natural fibers in terms of their mechanical properties, and Sienkiewicz et al. [27] discussed whether natural fillers can be used to modify the epoxy mixtures.

Although much information has been conducted on natural fiber-filled polymer composites, it has been reported that experimental studies examining the synergistic effect of recycled organic fillers (walnut shells, tree leaves) and glass fillers in unsaturated polyester matrices are scarce. The majority of the previous literature dwells on natural or synthetic reinforcements separately. Hence, this gap is filled by the current study, where the behavior of hybrid composites incorporating both agricultural waste materials and fiberglass is aimed at balancing performance and environmental impact.

The objective of the current study is to experimentally characterize the mechanical behavior of polyester reinforced by hybrid fibers, namely, synthetic glass fibers and natural agricultural waste fillers (walnut shells and tree leaves), with theaim to improve material performance, as well as to encourage the sustainable use of wastes. Where the objectives are:

1. To make composite samples with unsaturated polyester resin with different proportions of glass fiber, crushed walnut shell, and particles of tree leaves.
2. To conduct mechanical tests (tensile and flexural) on the prepared specimens according to the ASTM standards.
3. To compare the mechanical properties of hybrid composites, single-fiber composites, and neat polyester.
4. To determine the influence of various types of natural fillers and bending resistance using tensile strength and weight percentage.
5. To determine the possibilities of hybrid reinforcement as an ecologically-friendly and efficient mechanical solution in composite design.

The research will start with the introduction to the objectives of the study and the methodology used in the experimental-computational research, followed by a description of the contents of the study, research methods, and procedures. The most significant issue in the results and discussion is the effects of recycled natural fibers on reinforcement.

2. Materials and Methods

2.1. The Materials

A matrix of unsaturated polyester resin is reinforced with fiberglass, waste nut shell powder, and tree leaf particles, respectively, to form the composite materials studied in this study. Sustainable practices, waste reduction, and environmental pollution mitigation are all supported by using these waste materials as reinforcing agents. The materials that were used are summarized below

2.1.1. Polyester resin

As a kind of thermal resin, polyester has many applications and is inexpensive, making it a popular ingredient in composite materials. The resin was mixed with the hardener, which is of the Type of ethyl methyl ketone peroxide, at a ratio of 3 g per 100 g of polyester, a transparent liquid material purchased from resin sales centers manufactured by a Turkish company (Eskim). You can see the resin and hardener in Fig. 1. ESKIM ES-1060 is widely employed in thermoset composite applications due to its favorable processing characteristics and balanced mechanical properties. According to the technical datasheet provided by the manufacturer, the resin exhibits a tensile strength of approximately 73 MPa and a flexural strength of about 90 MPa, which serve as benchmark values for evaluating the performance of reinforced composites. The resin also has a density in the range of 1.10 to 1.20 g/cm³.

2.1.2. Glass fiber

Among the many fields that make use of glass fibers are building, transportation, aerospace, and defense. Reinforcing plastic composites, or used alone as thermal insulation, can be continuous or discontinuous and woven [28]-[30]. In this study, mat-type fiberglass was used as shown in Fig. 2.

2.1.3. Walnut shells and tree leaves

The walnut shells and tree leaves that were no longer needed were gathered, washed, and then air-dried to eliminate any loose particles. Fig. 3(a) and Fig. 4(a) show the cleaned walnut shells and tree leaves. Fig. 3(b) and Fig. 4(b) show the powdered walnut shells and tree leaves that were ground into a fine powder using an electric mill and sieved to ensure a consistent distribution of particle sizes. The density of natural fiber and tree leaves used is 860 and 540 Kg/m³, respectively.

Figure 1. Polyester.

Figure 2. Mat-type fiberglass.

2.2. Making Composites and Preparing Samples

One of the most common methods for making fiber-reinforced polymer composites is compression molding, but specimens have been manufactured using the hand placement method instead [31], [32]. Casting parts were produced by following the steps. First, a mixture of 3 wt % hardeners and polyester was mixed in the glass beaker. After that, ground walnut and tree leaves, each representing 10% and 20% of the total weight, respectively, were added to the mixture according to the proportions mentioned in Table 1. These materials are mixed well using a mechanical stirrer so that the reinforcements are evenly distributed throughout the material. Until they get a homogeneous mixture, to ensure that the mechanical properties of the composites were not compromised, the gases from the resulting mixtures were carefully degassed in a vacuum chamber to remove any trapped air bubbles [33]. A portion of them was added to the casting mold after the mold was coated with an oily substance to prevent adhesion of the mold and facilitate the extraction process after solidification. Finally, fiber mats (fiberglass) were cut to the exact dimensions of the mold and placed over the mixture in the mold using a brush. A roller was used over the mats to eliminate air bubbles. The process is repeated, applying resin and mats according to the number of layers of the selected fiberglass until the desired thickness is reached. The splint is then left to heal for a while before being removed. The samples are then cut using a CNC machine [34].

2.3. Classification of Samples

The samples were divided into fourteen categories, as illustrated in Table 1.

(a) (b)

Figure 3. Cleaned and powdered walnut shells.

(a) (b)

Figure 4. Cleaned and powdered tree leaves.

Table 1. Classification of samples and their components.

Samples groups	Components
G0	100%polyester
G0T10	90%polyester+10%tree leaves
G0T20	80%polyester+20 %tree leaves
G0N10	90%polyester+10 % walnut shell
G0N20	80%polyester+ 20 % walnut shell
G0TN	80%polyester +10%treeleaves+ 10% walnut shell
G1	polyester +one layer of fiberglass
G2	polyester+ two layers of fiberglass
G1T	80%polyester+ one layer of fiberglass +20%tree leaves
G2T	80%polyester+two layers of fiberglass +20%tree leaves
G2N	80%polyester+ two layers of fiberglass +20% walnut shell
G1TN	80%polyester + one layer of fiberglass +10%tree leaves+10% walnut shell

G1N	80%polyester+ one layer of fiberglass +20%walnut shell
G2TN	80%polyester+ two layers of fiberglass + 10%tree leaves+10% walnut shell

2.4. Type of Samples

In this research, two models were manufactured to test the hybrid composite material:

2.4.1. Tensile specimen

The ASTM (American Society for Testing and Materials) Standards D-638 were followed in the preparation and testing of the tensile test specimens [35], as shown in Fig. 5 and in Fig. 6.

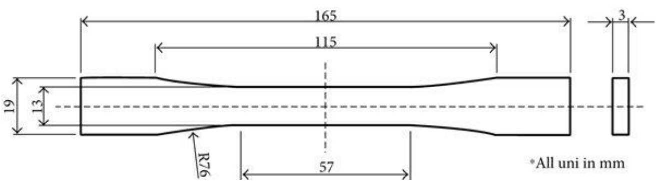

Figure 5. The tensile samples' dimensions.

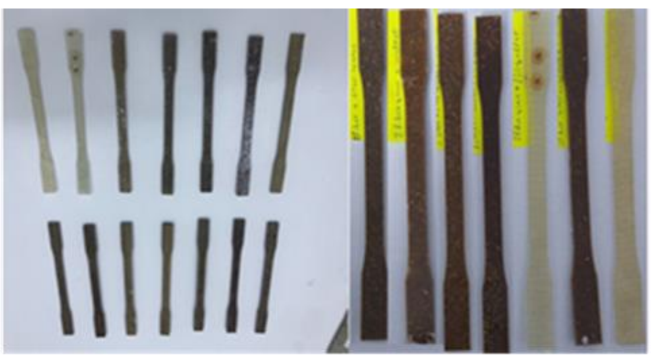

Figure 6. The tensile samples.

2.4.2. Flexural test specimen

All the composite specimens were of rectangular shape, having a length of 80mm x 15mm x 5mm, the dimensions according to ASTM D790 [36] as shown in Fig. 7.

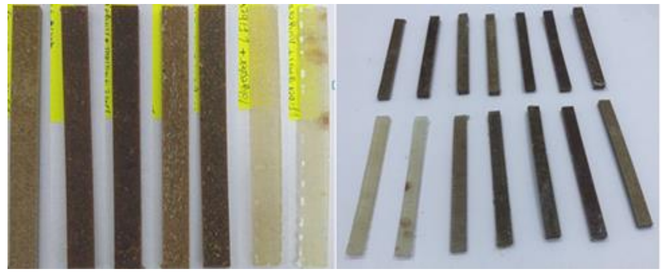

Figure 7. The bending samples.

All tests were conducted at 25°C to eliminate the effects of temperature fluctuations on the mechanical behavior of the samples. After the tests, specimens were visually examined to identify the failure mechanisms. The deformation and failure patterns were documented and analyzed to better understand the mechanical response of the composites under tensile load. Fig. 8 shows the uniaxial tensile testing setup, while Fig. 9 presents the specimens before and after failure during the test.

Figure 8. The uniaxial tensile machine test.

3. Experimental Tests

3.1. Tensile Testing for Property Prediction of the Samples

to conduct uniaxial tensile tests. A minimum of three valid tests were performed per material composition to ensure reliability and to account for possible variations in sample preparation. This practice aligns with standard material testing procedures and supports the statistical validity of the results. The specimens were tested using a constant crosshead rate of 1.0 mm/min to obtain accurate measurements without inducing unnecessary strain.

3.2. Three-Point Bending Flexural Testing

Composite materials' flexural strength and stress-strain response were estimated using a three-point flexural test. A universal testing apparatus was used in the experiments, along with a three-point bend fixture and an instrument control panel, to perform the three-point bending tests, as illustrated in Fig. 10.

Consideration of these characteristics is crucial for designing flexural test specimens that accurately reflect the material's typical behaviour under bending loads. When a material's limits are exceeded by strain or elongation, failure happens. The specimens were subjected to bending on two supports, with a 50 kg load applied at the midpoint using a crosshead moving at a speed of 2 mm/min. The maximum stress during bending was then calculated. The control panel registered the highest level of stress in order to avoid excessive loads and fractures. The findings are succinctly presented in Fig. 11.

Figure 9. Tensile samples before and after failure during the test.

4. Results and Discussion

4.1. Tensile Test Results

The tensile behavior of the unreinforced polyester matrix (G0) and its composites reinforced with one (G1) and two (G2) layers of woven fiberglass is illustrated in Fig. 12. The results clearly show a significant improvement in tensile strength with the inclusion of fiberglass layers. Specifically, the addition of one layer of woven fiberglass enhanced the tensile strength by 44% compared to G0, while two layers led to an 81% improvement. This enhancement is primarily attributed to the acid-base interactions and surface energy of the glass fibers, which promote better interfacial adhesion with the polyester matrix [37]. The strong fiber-matrix bonding facilitates efficient stress transfer under loading, which in turn enhances the composite's mechanical performance. Additionally, increasing the number of fiberglass layers contributes to greater structural integrity, leading to higher stiffness, durability, and tensile strength.

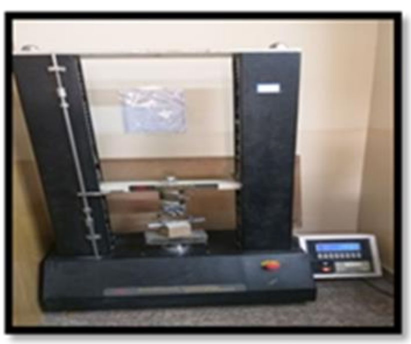

Figure 10. Three-point bending machine test.

Figure 11. Bending samples before and after failure during the test.

These findings are consistent with previous studies. For example, [38] reported improved mechanical and physical properties when incorporating oil palm mesocarp fibers into a polyester matrix, and [39] demonstrated enhanced mechanical, morphological, and thermal behavior in composites reinforced with woven polyester fibers.

In contrast, the incorporation of ground natural fibers such as tree leaves and walnut shells—in combination with fiberglass reinforcement—resulted in a reduction in tensile strength, as shown in Figs. 13 to 16. This decline becomes more pronounced as the proportion of natural fibers increases. Among the hybrid samples, those reinforced with walnut shell powder exhibited better performance compared to those with tree leaf particles. This can be attributed to relatively better interfacial bonding and possibly higher rigidity of walnut shell particles. However, both types of natural fillers showed inferior mechanical performance when compared to fiberglass alone. As indicated in Table 2, adding 10% walnut shell to a polyester matrix reinforced with one layer of fiberglass led to a 40.3% decrease in tensile strength, whereas incorporating 10% tree leaves resulted in a drastic 127% reduction.

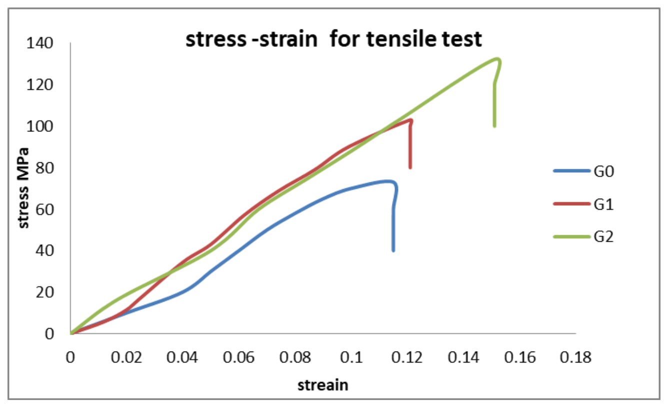

Figure 12. Stress-strain behavior of composite material under tensile test.

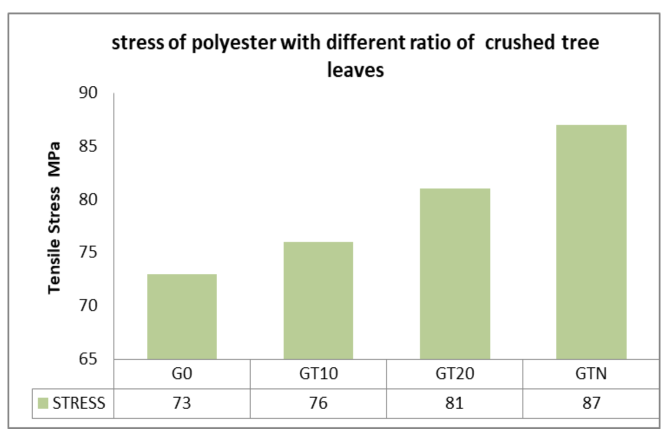

Figure 13. Stress value of polyester with different ratios of crushed tree leaves.

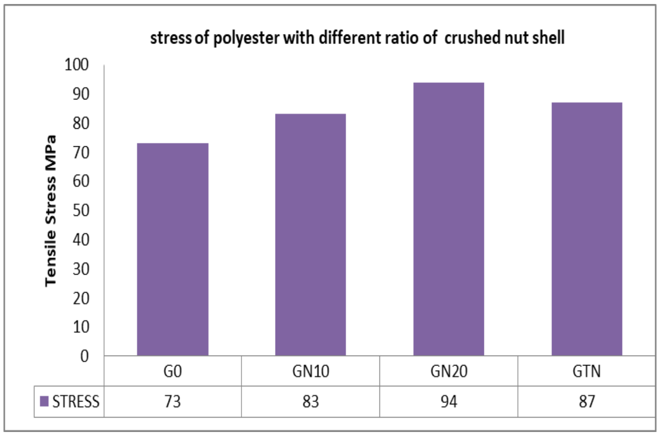

Figure 14. Stress value of polyester with different ratios of crushed walnut shell.

The degradation in mechanical properties can be explained by several contributing factors: Poor interfacial bonding between natural fillers and the polyester matrix, irregular dispersion of the natural particles, the intrinsically lower mechanical strength of natural fibers compared to synthetic ones, and possible matrix discontinuities or weakening introduced by the added particles.

These observations align with findings from [40]-[42], who highlighted the challenges of achieving strong and consistent bonding in hybrid composites incorporating natural reinforcements.

Table 2. Experimental results.

Sample	Tensile Stress Mpa	Tensile Strain MPa	Bending Stress Mpa	Bending Strain
G0	73	0.115	31	0.21
G1	103.4	0.121	41	0.237
G2	132.2	0.151	46	0.35
G1T	33.83	0.103	32.06	0.06
G2T	43	0.063	28.5	0.094
G1N	52	0.118	37	0.12
G2N	69.38	0.124	29	0.098
G1TN	40	0.103	28.46	0.225
G2TN	36	0.0736	12.99	0.18

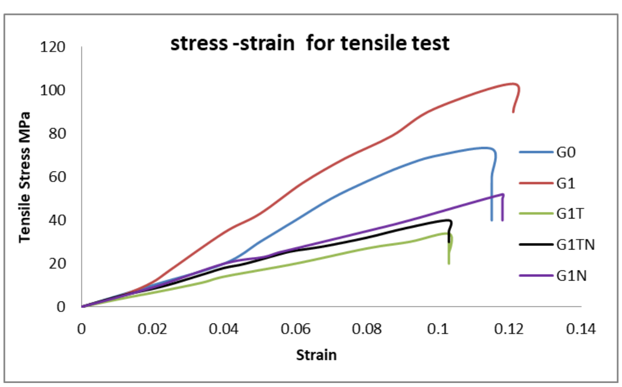

Figure 15. Stress-strain behavior under tensile test for polyester with different ratios of crushed walnut shell.

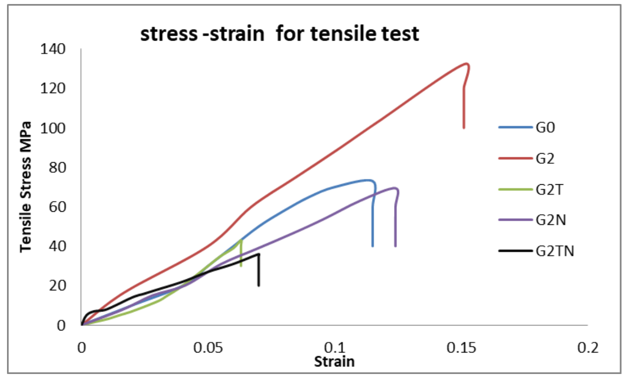

Figure 16. Stress-strain behavior under tensile test for polyester with different ratios of crushed tree leaves.

4.2 Bending Test Results

It was revealed that one or two layers of fiberglass greatly enhanced the flexural properties of polyester, as shown by the results of the bending test. Fig 17 indicates that the reinforcements of polyester by one and two layers of woven fiberglass increased the bending strength by 32.2 and 48.3 percent, respectively. These developments affirm that fiberglass boosts the structural and thermal stability of polyester composites, which can be used in different engineering designs [42]. Some industries can either gain or have difficulties with the utilization of hybrid composite materials that mix glass fibers with natural fibers. The benefits are less environmental impact, enhanced sustainability, lowered cost, and acceptable mechanical performance. The disadvantages can, however, be 1) the hydrophilic property of natural fibers and 2) the trouble in attaining the correct bonding with the polymer matrix. The given issue is evident in the present study. The flexural performance of the composite reinforced with crushed walnut shells, as depicted in Fig. 18 and Fig. 19, was comparatively good compared to the ones reinforced with crushed tree leaves at the same ratios. The composites that were made using the walnut shell resulted in greater bending strength, a feature that demonstrates greater compatibility and rigidity. The data given in Table 2 also confirms these trends, and is not surprising considering the results of other researchers [40], [41].

Additionally, the adverse effect on bending performance of natural fibers would be more pronounced when the effects are analyzed quantitatively. The flexural strength of polyester reinforced with 1 layer of fiberglass reduced by 27.8 and 10.8%, respectively, when crushed tree leaves and crushed walnut shells were added, as shown in Fig. 18, Fig. 19, and Table 2. In the case of 2-layered fiberglass reinforced composites, the reduction was 8.7% and 6.8%, respectively. These findings confirm that although natural fibers are capable of adding to the concept of sustainability, they also can damage the mechanical performance because of the poor interfacial adhesion and the ability to absorb moisture, as found in [39], [41].

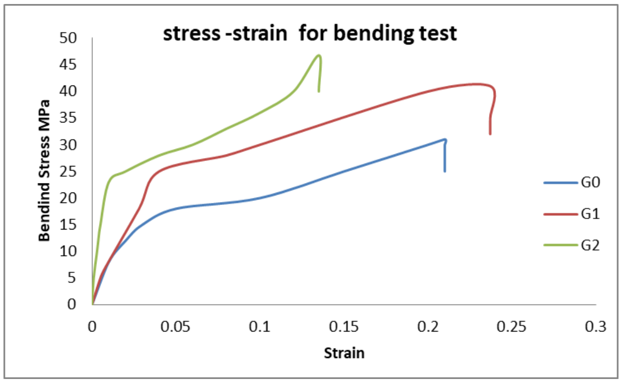

Figure 17. Stress-strain behavior curve of composite material under bending test.

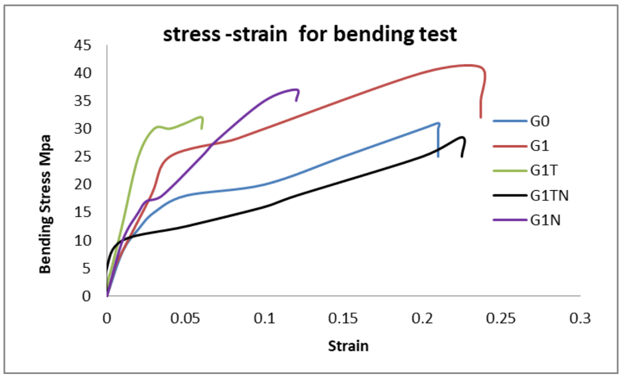

Figure 18. Stress-Strain behavior under bending test for polyester with different ratios of crushed tree leaves.

5. Conclusions and Future Works

The results demonstrate that the incorporation of one and two layers of woven fiberglass markedly improves the tensile strength of polyester composites by 44% and 81%, respectively, which can be attributed to the high surface energy and favorable acid–base characteristics of glass fibers that enhance interfacial adhesion with the polyester matrix. Conversely, the addition of ground natural fibers derived from tree leaves and walnut shells to fiberglass-reinforced polyester leads to a reduction in tensile strength; however, hybrid composites reinforced with walnut shells exhibit superior mechanical performance compared to those containing ground tree leaves. In terms of flexural behavior, the bending properties of polyester are significantly enhanced by the inclusion of one or two fiberglass layers, resulting in increases in bending strength of 32.2% and 48.3%, respectively, owing to improved flexural rigidity and thermal stability. Although hybrid composites combining glass and natural fibers offer advantages such as cost-effectiveness, environmental friendliness, sustainability, and acceptable mechanical properties, they may also present challenges related to increased hydrophilicity and interfacial compatibility between the polymer matrix and natural reinforcements. Furthermore, when both fiber types are incorporated simultaneously, a decrease in bending resistance is observed, particularly in composites containing ground tree leaves, whereas walnut shell–reinforced hybrids demonstrate comparatively better mechanical behavior. Overall, the findings indicate that hybrid composite materials incorporating ground walnut shells exhibit enhanced mechanical performance relative to those reinforced with ground tree leaves, suggesting their greater potential for future development and application.

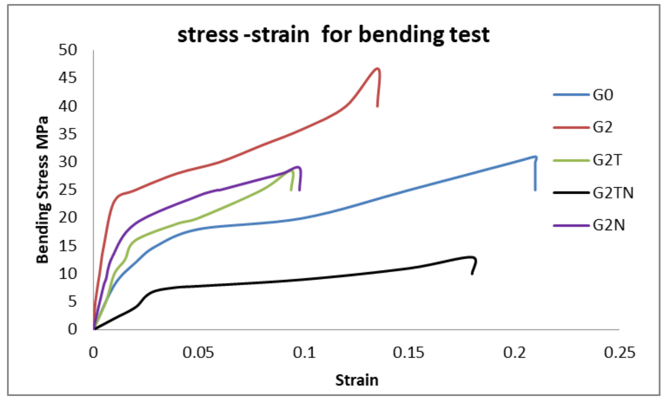

Figure 19. Stress-strain behavior under bending test for polyester with different ratios of crushed walnut shell.

Future work may focus on optimizing the ratio and distribution of natural fillers to further improve the mechanical properties and durability of hybrid composites. Investigating surface treatments or chemical modifications of natural fibers could enhance their compatibility with the polyester matrix and reduce moisture sensitivity. Additionally, exploring alternative bio-based resins and nano-fillers may contribute to developing more sustainable, high-performance composite materials. Long-term environmental aging, biodegradability studies, and life cycle assessment are also recommended to evaluate the real-world performance and sustainability impact of these hybrid composites for potential industrial applications.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Zahra Khalid proposed the research problem. Zahra Khalid, Zaineb Wared Metteb, Nazik Abdulwahid Jebur, and Hassan Shokrollahi prepared the samples, tested them, and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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